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Sensors and Actuators A 96 (2002) 43–52

SENSORS AND ACTUATORS A PHYSICAL

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Novel bulk acoustic wave hammer to determinate the dynamic response of microstructures using pulsed broad bandwidth ultrasonic transducers

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Received 2 April 2001; received in revised form 9 July 2001; accepted 1 October 2001

Abstract

A novel testing technique to determinate the dynamic response of the microstructure is presented. In this study, a bulk acoustic wave (BAW) hammer generated by a pulsed ultrasonic transducer is used to excite the microstructures. Thus, the dynamic response of the microstructure in a wide frequency range is excited. Based on this novel method and test apparatus, the dynamic response of the microstructure including the resonant frequency, mode shape and the modal damping of the microstructure can be measured in a single excitation. Experimental results of the microbeams with different length agree well with theoretical predictions. In summary, the proposed BAW hammer technique has the following advantage: the sample preparation for this approach is very easy since it is not necessary to deposit an additional film for thermal or electrical purpose. In this regard, the experimental results of this technique are more accurate since there is no additional film to influence the dynamic behavior of the test sample. Moreover, there is no uncertain side effect such as thermal and acoustic coupling, caused by this approach. Since the test apparatus is also very simple, this approach has the potential to do the on-line test for batch production.

Keywords: Bulk acoustic wave hammer; Dynamic response; Microstructures; Ultrasonic transducer; Impulse excitation

1. Introduction

Microsensors and actuators are the key components in the microelectrical mechanical systems. The performance of microsensors and actuators correlate closely with their dynamic mechanical properties. For instance, the bandwidth, resolution, and response time of some microsensors is determined by their mechanical resonance [1]. The output characteristic of microactuators including force amplitude and operating frequency is also determined by their dynamic behavior [1]. Therefore, the testing method to evaluate the dynamic behavior of the microtransducers in MEMS is very important. Several excitation and detection approaches have been proposed to characterize the dynamic response of the microstructure. Based on the measured dynamic response, vibration characteristics such as the natural frequencies and the mode shapes of the microstructure can be obtained. Moreover, the material properties including residual stress [2], Young's modulus [3–9], and fatigue property can also be determined.

The measured dynamic response of the microstructure will be affected by the excitation technique. In general, the existing dynamic tests can be classified into three categories according to their excitation approaches. The first approach is to drive the microstructure through built-in electrostatic electrodes [2–4]. It is necessary to deposit an additional conducting film if the structure is made of dielectric materials. The effect of the additional film on the dynamics of the test structure must be considered, especially for the determination of the thin film material properties. Secondly, a photo thermal load through an external source [5,6] is exploited to excite the microstructure. In this case, an additional metal layer is required to coat on the microstructure. Hence, the variation of the mechanical properties resulted from the thermal effect can not be ignored. Thirdly, the microstructure is driven by a bulk PZT transducer externally [7–10]. The disadvantage of this approach is the dynamic coupling between PZT transducers and the microstructure. Moreover, the PZT transducer in [8] can not excite the microstructure in the vacuum environment acoustically. In [10], a swept-sine signal is used to drive microstructures. However, this approach is only applied for the millimeter dimensional microstructures because of the limitation of PZT transducers.

Presently, the ultrasonic transducer has been widely used in nondestructive testing and medical diagnostic [11–15]. In this study, a BAW hammer using pulsed broad bandwidth

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0924-4247/02/$ – see front matter
PII: S0924-4247(01)00758-0

ultrasonic transducer is exploited to drive the microstructure. The transducer can generate an excitation of broad bandwidth and constant magnitude on microstructures to satisfy the requirement for vibration modal test. After the impulse excitation, the dynamic characteristics of the microstructure including the resonant frequency, mode shape, and the modal damping factors will be measured using laser Doppler vibrometer (LDV). The test set-up is very simple for this approach. There is no additional film required to deposit on the test structure; meanwhile, the side effects comes from the additional film can be prevented. This approach can be applied to study the air effect on the dynamic response of microbeams in a vacuum environment as well.

2. Theory

2.1. Bulk acoustic wave (BAW) hammer using pulsed ultrasonic transducer

The impulse excitation is one of the primary techniques used in the conventional vibration test to determine the dynamic behavior of structures [16]. An impact hammer is used to generate the impulse excitation after striking at the structure. The impulse with a specific amplitude A and duration Δt can excite all the vibration modes of a structure within a certain frequency range. For a constant load, the effective frequency range is inversely proportional to the duration Δt. It is necessary to induce a pulse with a shorter Δt to raise the testing frequency range. However, due to the possession of higher natural frequencies for microstructures, conventional impact hammer is hardly applicable to the vibration test. Moreover, it is difficult to apply impact hammer to the microstructure because the mismatch of their size. In this study, a pulsed BAW is exploited to excite the microstructure during the vibration test. As illustrated in Fig. 1a broad bandwidth ultrasonic transducer is used to generate the BAW. In short, the impact hammer is replaced by a BAW hammer (the broad bandwidth ultrasonic transducer).

Generally, the transducer consists of an active PZT element, and three passive layers such as backing, matching and acoustic lens layers [11]. When the PZT ceramic driven by a pulse voltage, the transducer will produce an impulse time response operated by its thickness extensional mode [11]. In this regard, the characteristics of the BAW hammer are determined by the bandwidth, ringdown time, and peak-to-peak excitation amplitude of the transducer. A typical example of impulse waveform and power spectrum of the transducer is shown in Fig. 1b and c. The waveform and frequency spectrum of the transducer used in this study has been defined by the The American Society for Testing and Materials (ASTM) code E1065. According to this code, the waveform duration Δt is defined as the -20 dB level amplitude of peak, as shown in Fig. 1b. The central frequency f_c in the frequency response of the waveform is expressed as $f_c = (f_u + f_l)/2$. As indicated in Fig. 1c, the parameters f_l and f_u are upper and lower frequencies where the power spectrum drop -6 dB from its peak. The bandwidth of the BAW hammer (BW) is defined as $\mathrm{BW} = 100 \times (f_u - f_l)/f_c$. However, the energy level of the transducer required for the impulse test is not restricted to -6 dB. Hence, the effective bandwidth for impulse test is wider than BW. The natural modes of the microstructure within the effective bandwidth will be excited. Based on the proposed method, it is possible to design a transducer to generate an impulse with a specific waveform. Thus, the natural behavior of the microstructure within a specific frequency range can be determined.

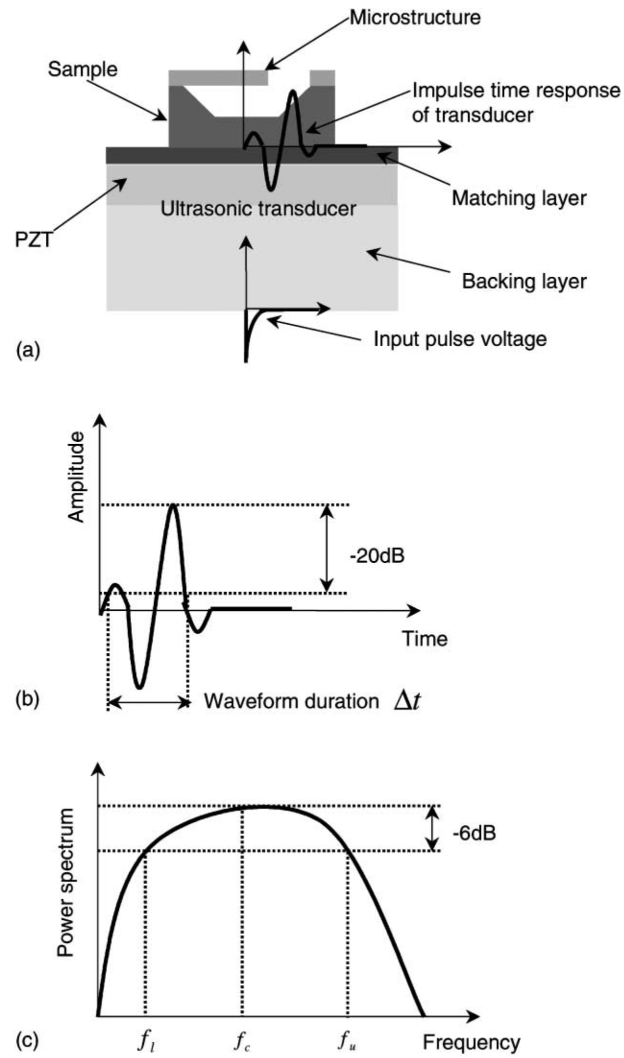

Fig. 1. A schematic diagram of the bulk acoustic wave (BAW) hammer applied to microstructures using pulsed broad bandwidth ultrasonic transducer, (a) the proposed BAW hammer model, (b) the impulse time response of transducer, and (c) the impulse frequency response of transducer.

2.2. Dynamic properties of microstructure

The micromachined cantilevers are used as the test structures in this study. The undamped natural frequency f_n of a cantilever beam is given by [17]

$$f_n = \frac{1}{2\pi}\lambda_n^2\sqrt{\frac{Eh^2}{12\rho L^4}} \quad (1)$$

where E, ρ, L, and h are the Young's modulus, density, length, and thickness of the cantilever, respectively. The parameter λ_n is the eigenvalue of the problem and is given by the solution to $\cosh(\lambda_n)\cos(\lambda_n) + 1 = 0$. In Eq. (1), n is an integer indicating the nth natural mode. The shape $V_n(x)$ of the beam at bending modes described by [10] is expressed as

$$V_n(x) = A_n[\sin(\lambda_n x) - \sinh(\lambda_n x) - C_n\cos(\lambda_n x) + C_n\cosh(\lambda_n x)] \quad (2)$$

where

$$A_n = \frac{\sinh\lambda_n - \sin\lambda_n}{2(\cosh\lambda_n + \cos\lambda_n)}, \quad C_n = \frac{\cosh\lambda_n + \cos\lambda_n}{\sinh\lambda_n - \sin\lambda_n}$$

Eq. (2) was normalized, so as to give an unity displacement at the free end of the microbeams.

3. Experiments and results

3.1. Experiments

In application of the proposed BAW hammer technique, silicon dioxide cantilever beams and plates were fabricated on the (1 0 0) oriented silicon substrate. The thermal oxide film was grown on the (1 0 0) wafer at first. The oxide film was patterned into different geometry by buffered HF after photolithography. The substrate under the microstructures was etched anisotropically using TMAH solution. Fig. 2 shows the photographs of typical cantilever beams and plate fabricated through the above processes. The test microcantilevers were 6 μm wide and 1.1 μm thick, and their length ranged from 20 to 80 μm. The gap between microcantilevers and the substrate was 55 μm after the bulk etching to prevent the squeeze film effect.

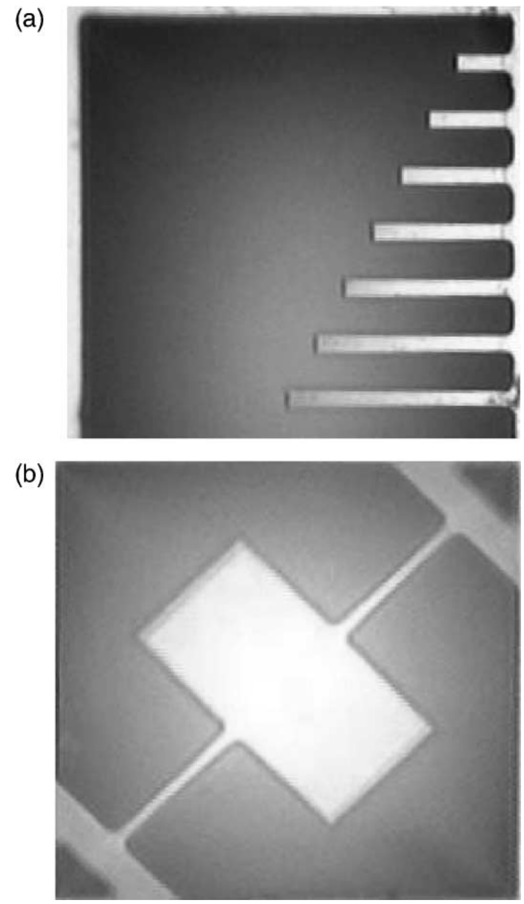

Fig. 2. The photographs of the testing sample, (a) SiO_2 cantilever beams, and (b) SiO_2 torsional mirror plate.

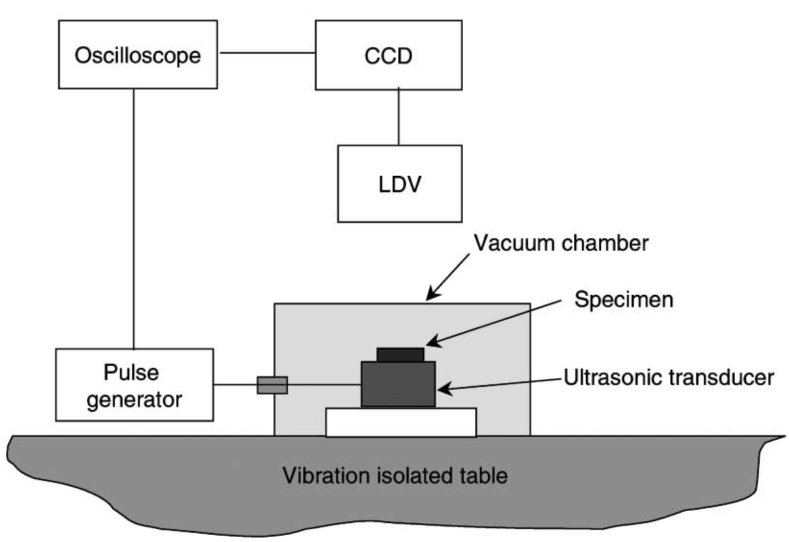

Fig. 3. The experimental set-up for BAW hammer test.

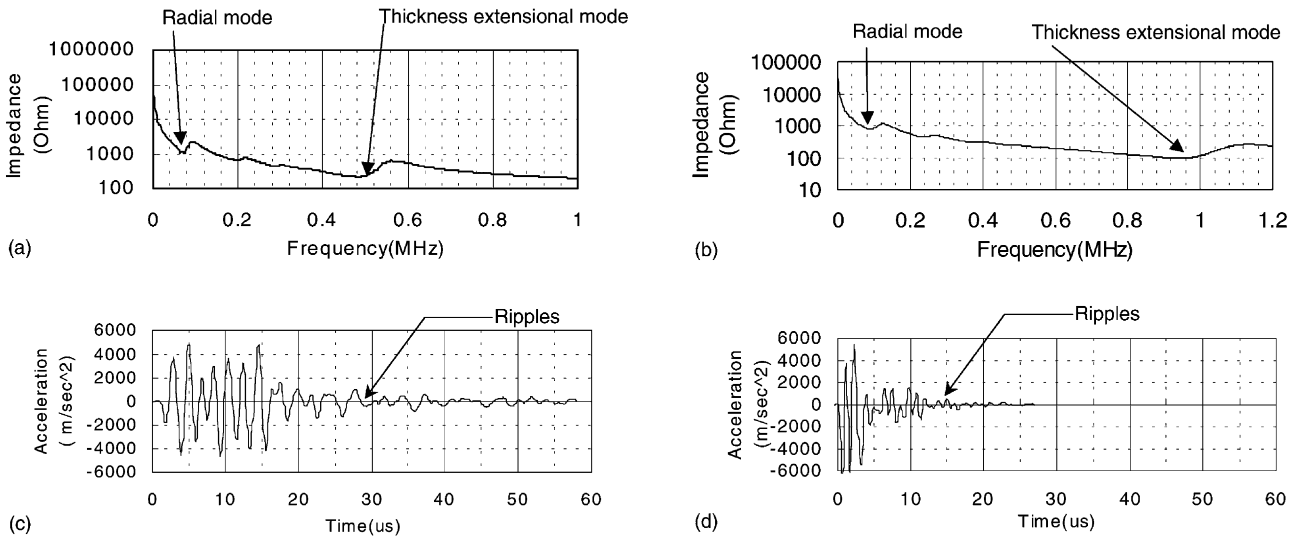

Fig. 4. The characteristics of different hammers, (a) impedance curve of $f_c = 540$ kHz, (b) impedance curve of $f_c = 1$ MHz, (c) impulse time response of $f_c = 540$ kHz, and (d) impulse time response of $f_c = 1$ MHz.

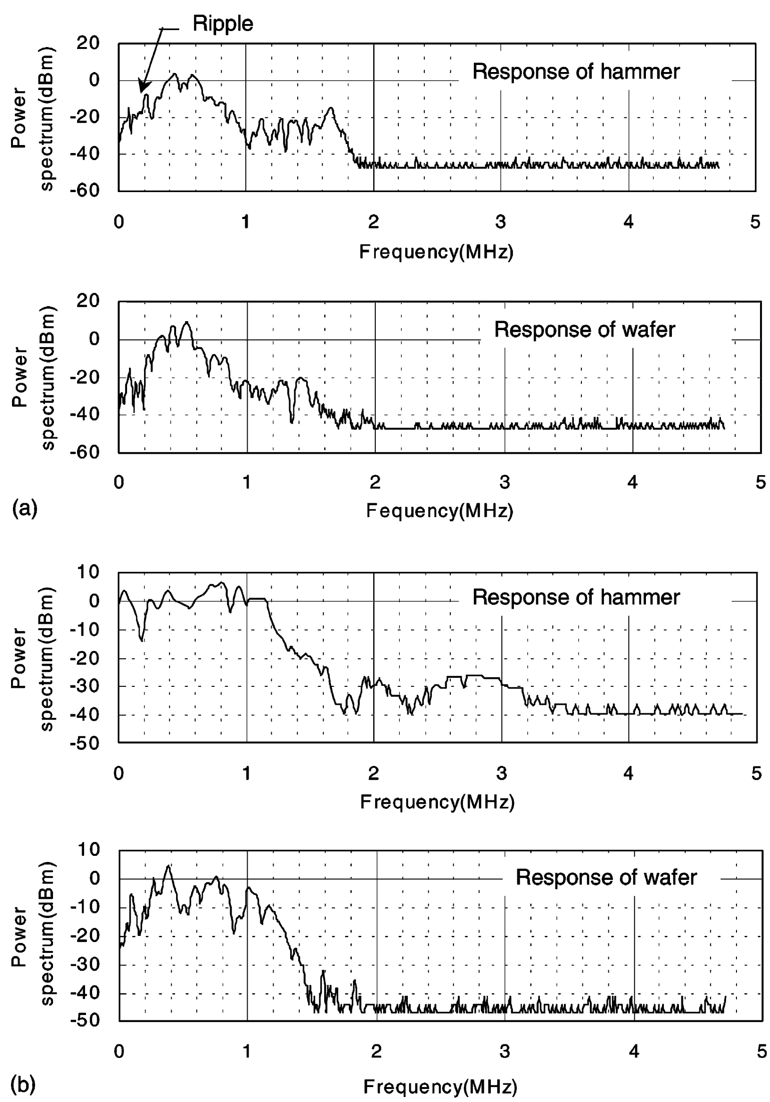

Fig. 5. The measured frequency response of the hammer and wafer after excited by the hammer with (a) $f_c = 540$ kHz, and (b) $f_c = 1$ MHz.

The experimental set-up for recording the dynamic response of microstructures using the BAW hammer technique is illustrated in Fig. 3. The sample was mounted on the ultrasonic transducer by wax or sticky tape. The ultrasonic transducer generated a BAW after excited by a pulse voltage. The high voltage pulse generator system in Fig. 3 was used to produce a very short pulse voltage shown in Fig. 1a to provide a broad bandwidth frequency spectrum to the ultrasonic transducer. Afterwards, the sample experienced a broad bandwidth frequency range excitation. The pulse generator system in Fig. 3 can also be replaced by a function generator together with a power amplifier. Finally, the dynamic response of the microstructures was measured from the LDV system. And the time and frequency response of the microstructures can be recorded and analyzed in the oscilloscope or frequency analyzer. The vacuum chamber was established in the experiment to perform the dynamic test in various ambient pressure.

The characteristics of the BAW hammer would significantly affect the testing result of the microstructure. The performance of the BAW hammer correlates closely with the design of the pulse generator and transducer. In the experiment, the voltage amplitude and the pulse repetition rate were well controlled by a commercial pulse generator. The pulse generator has an output impedance of 50 ohm. The pulse applied on the ultrasonic transducer was 175 V in amplitude, 0.23 μs in width, and 1 kHz in repetition rate. The BAW hammer composed of PZT disc plus backing layer design with different central frequencies f_c was studied. The measured electrical impedance curves of the hammer with their central frequencies f_c at 540 kHz and 1 MHz, respectively are shown in Fig. 4a and b. The lowest point indicated in Fig. 4a and b represents the thickness extensional mode of the transducer [18]. The active elements of the 540 kHz and 1 MHz hammers were PZT4 disc with diameter 30 mm and PZT5A disc with diameter 20 mm, respectively.

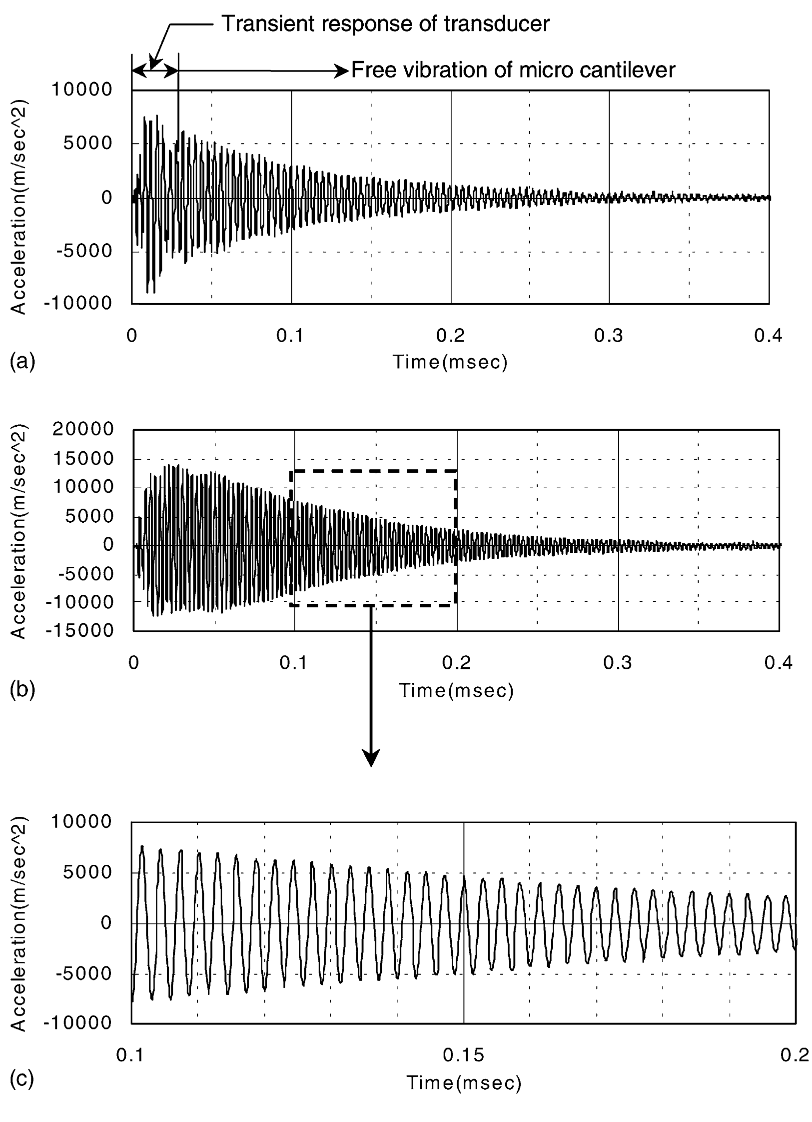

Fig. 6. The measured impulse time response of 1.1 μm thick, 6 μm wide test cantilevers with length (a) $L = 60$ μm, (b) $L = 50$ μm, and (c) a zoom in of (b).

Moreover, the acoustic impedance of the backing layer is 5.6 M Rayls and its velocity is 1280 m/s. The impulse time responses of these two hammers measured at the center of the transducers are shown in Fig. 4c and d. Fig. 4c and d showed that the hammer with $f_c = 1$ MHz has shorter duration Δt than the one with $f_c = 540$ kHz. The thickness extensional mode was damped out first, and only the low order radial modes still sustained in the response [19]. Hence, the low frequency radial modes of transducer induced some ripples at the end of waveform, as indicated in Fig. 4c and d.

The impulse frequency responses measured at the surface of both the hammer and the wafer are shown in Fig. 5. The agreement of the spectrum between the hammer and the wafer demonstrates that the energy was effectively propagated from the excitation source to the test sample. Moreover, the results also indicate that the f_c and the BW of an excitation can be adjusted by changing the transducer. The transducer with $f_c = 1$ MHz has broader frequency range than the one with $f_c = 540$ kHz. Hence, the transducer with $f_c = 1$ MHz would be selected as the excitation source of the BAW hammer in the experiment. The ripples in the first range of spectrum originated from the low frequency radial modes of the transducers [19]. These ripples would be damped immediately since the transducer employed in this

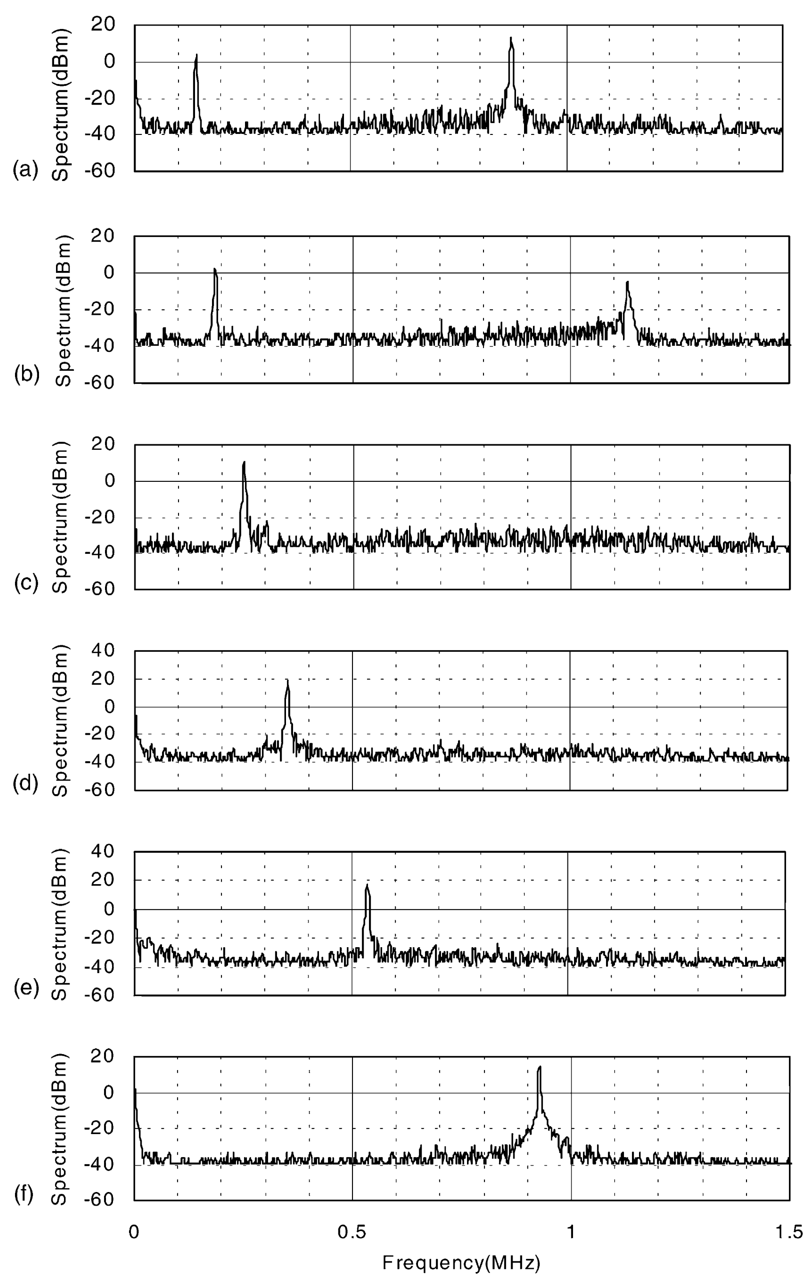

Fig. 7. The measured impulse frequency response of 1.1 μm thick, 6 μm wide test cantilevers when length L equal to: (a) 80 μm, (b) 70 μm, (c) 60 μm, (d) 50 μm, (e) 40 μm and (f) 30 μm.

study was designed to have the backing layer added to the PZT disc. Thus, the ripple would only be slightly coupled with the dynamic response of the microstructures.

3.2. Results

As shown in Fig. 6a and b, the free vibration of the cantilevers with $L = 60$ and 50 μm, respectively was recorded by the oscilloscope. The vibration of these beams were excited by a $f_c = 1$ MHz transducer. The laser spot was placed on the free end of the cantilevers. The first few cycles of the response were due to the dynamics of the transducer; thus, they would not represent the free vibration of the beam. After the beam started its free vibration, the response for a typical viscous damped system was obtained, as shown in Fig. 6. Moreover, the measured frequency spectrums of the microcantilevers after BAW hammer excitation are shown in Fig. 7. The results show that the fundamental frequency of the microcantilevers varied from 150 to 920 kHz when the beam length L decreased from 80 to 30 μm. In Fig. 7a and b, the second bending modes of the beam can also be measured. It is shown that this approach can excite the resonant frequency of the microstructures up to the MHz range.

In Fig. 8, the free vibration of a 60 μm long cantilever beam under various air pressure after excited by 1 MHz transducer was recorded. It is obtained that the free vibration of the beam was sustained for a longer period when the air pressure decreased from 780 Torr to 20 mTorr. Briefly, the viscous damping due to the air significantly dominates the quality factor of the microcantilever. Fig. 9a and b show the frequency spectrum associated with the time response in Fig. 8b and d, respectively. According to the frequency spectrum, the measured modal quality factors ranged from 80 to 5000 when the air pressure decreased from 780 Torr to

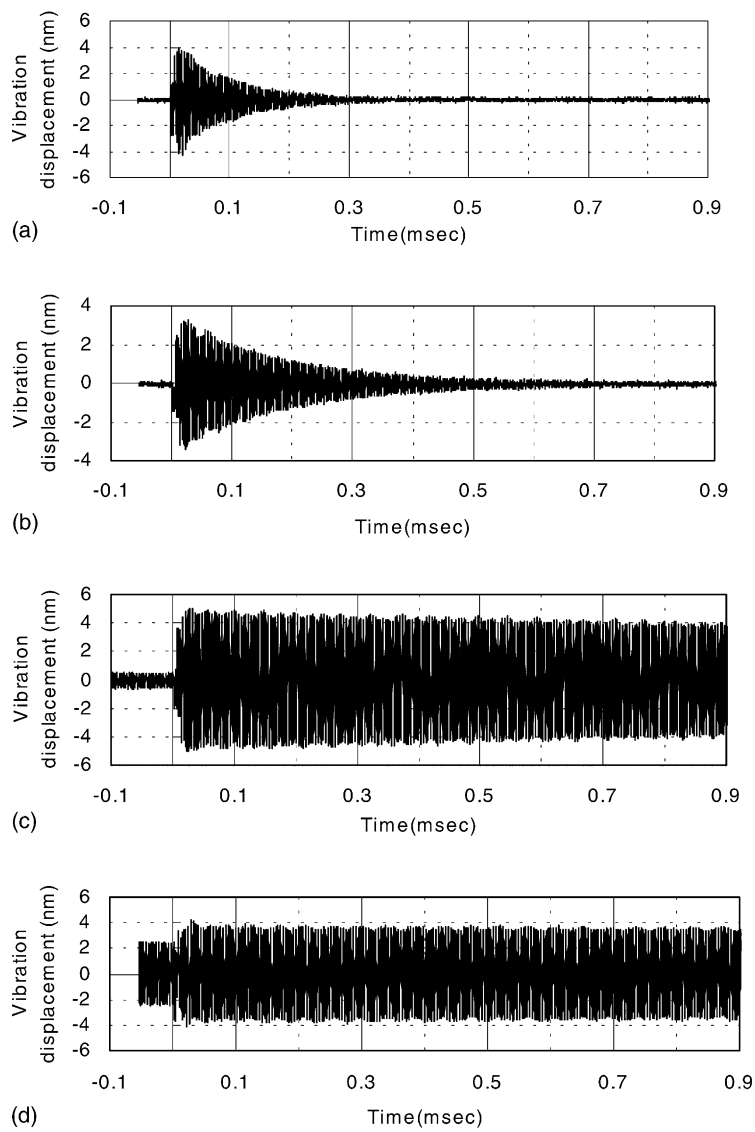

Fig. 8. The impulse time response of 1.1 μm thick, 6 μm wide, 60 μm long test cantilevers varied with different air pressure: (a) 780 Torr, (b) 75 Torr, (c) 1 Torr and (d) 20 m Torr.

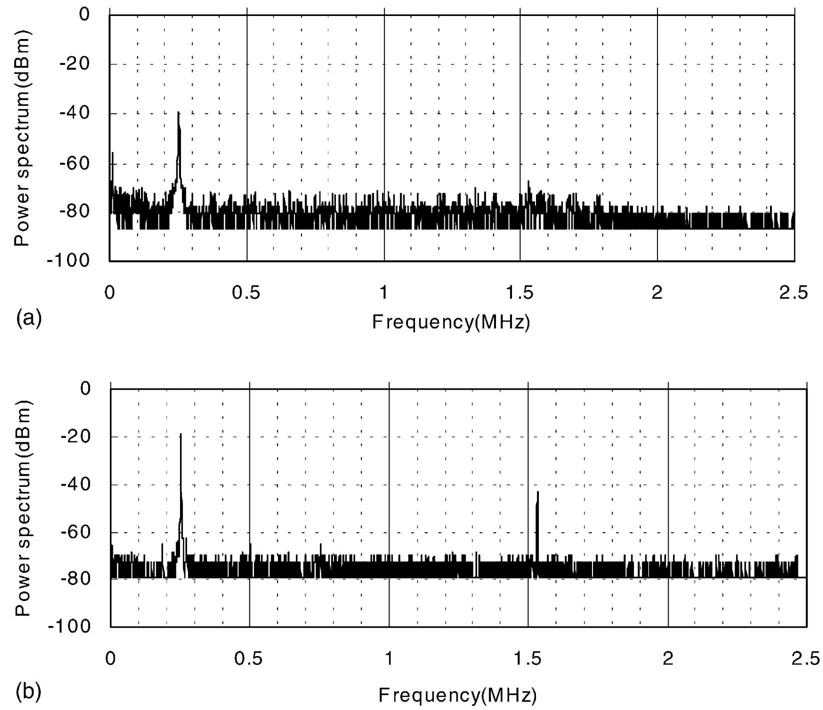

Fig. 9. The impulse frequency response of 1.1 μm thick, 6 μm wide, 60 μm long test cantilevers varied with different air pressure: (a) 75 Torr (b) 20 m Torr.

20 mTorr. In Fig. 9b, the second bending mode of the beam was obtained when air pressure dropped to 20 mTorr. Thus, the power spectrum signal of the proposed technique was improved at lower ambient pressure.

4. Discussion

The free vibration of a microstructure in both time and frequency domains is measured after the excitation of a

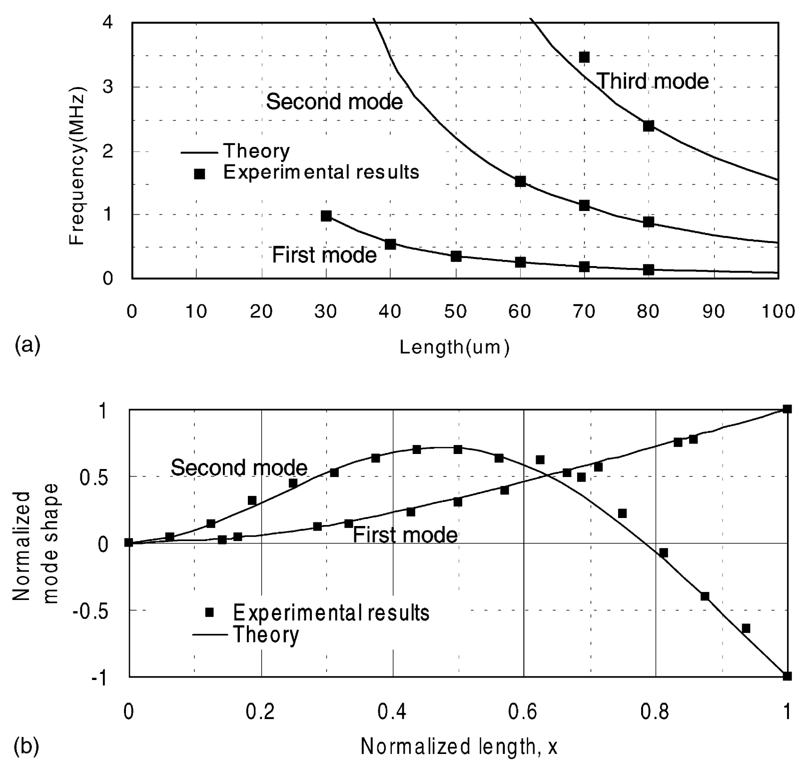

Fig. 10. Comparison of theoretical and experimental results, (a) natural frequencies of different bending modes, and (b) the mode shape of the first two bending modes.

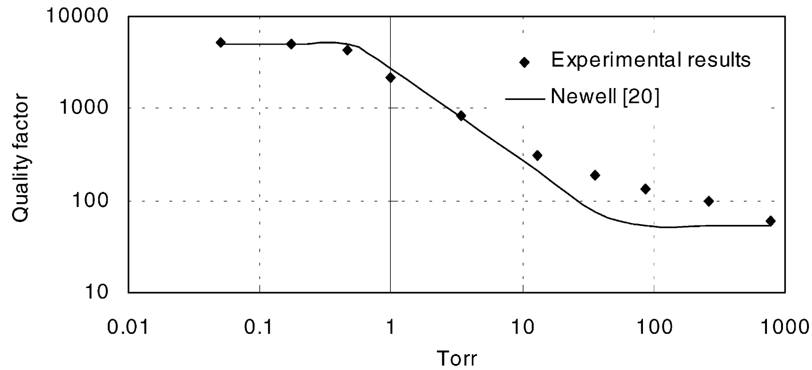

Fig. 11. Variation of the quality factor of the test beams with the ambient pressure.

BAW hammer. To verify the validation of the BAW hammer technique, the comparison between the measured resonant frequencies and the predicted ones is shown in Fig. 10a. The solid line was predicted by Eq. (1) based on the density and Young's modulus of microstructures known previously. Apparently, the experimental results agree well with the predicted ones. The deviation between the experimental and analytical results was from 2 to 6%. On the other hand, the variation of the natural frequency with the beam in different lengths can also be used to determine the Young's modulus of thin film. In this regard, the Young's modulus of the microbeam is obtained after curve fitting the data points in Fig. 10a to Eq. (1). The mode shape of microstructure can also be determined, after measuring the spectrum at different position of the beam. Comparison of the measured and predicted results for the first and second bending modes of a 80 μm long beam is shown in Fig. 10b. The data points represent the measured results and the solid lines were predicted by Eq. (2).

The equivalent modal damping (or quality factor Q) of the microbeam due to air effect described by [20] can be divided into three regions. In the near vacuum region, the intrinsic Q is independent of pressure and must be determined empirically. Under the atmosphere pressure region, gas is regarded as viscous fluid. Therefore, the relation of the Q and the dimension of the microbeam is determined by the Stoke's law [20]

$$Q = \left(\frac{h}{L}\right)^2 \left[\frac{b(E\rho)^{1/2}}{24\mu}\right] \quad (3)$$

where μ is the viscosity of the air and b the width of the microbeam. If the microstructure is operating under low pressure, the relation between the quality factor and the dimension of the microbeam becomes [20]

$$Q = 93\left(\frac{h}{L}\right)^2 \left[\frac{(E\rho)^{1/2}}{P}\right] \quad (4)$$

where P is the pressure of the air. In Fig. 11, the quality factor of first bending mode of $L = 60$ μm beam under various air pressure was also measured through the proposed technique. The experimental results agree well with the analytical results predicted by Eqs. (3) and (4).

5. Conclusion

In this research, a novel technique to determinate the dynamic response of the microstructure using pulsed broad bandwidth ultrasonic transducer was studied. The ultrasonic transducer excited by the impulse signal acting as a BAW hammer to provide broad bandwidth frequency excitation to the testing sample. Hence, the natural modes of the microstructure in the frequency power spectrum range will be excited along the direction of impact hammer. Experimental results demonstrated that this technique is a fast and promising approach for characterizing the dynamic behaviors of the microstructure. In summary, the proposed BAW hammer technique has the following advantage: the sample preparation for this approach is very easy since it is not necessary to deposit an additional film for thermal or electrical purpose. In this regard, the experimental results of this technique are more accurate since there is no additional film to influence the dynamic behavior of the test sample. Moreover, there is no uncertain side effect such as thermal and acoustic coupling, caused by this approach. Since the test apparatus is also very simple, this approach has the potential to do the on-line test for batch production.

Acknowledgements

The authors would like to express his appreciation to the Department of Ultrasonic Technology in Industrial Technology Research Institute (ITRI), the NSC Central Regional MEMS Center, the Electrical Engineering Department of National Tsing Hua University (Taiwan), Semiconductor Research Center of National Chiao Tung University (Taiwan), and the NSC National Nano Device Laboratories (Taiwan) in providing experimental facilities.

References

[1] B. Hok, K. Gustafsson, Vibration analysis of micromechanical elements, Sens. Actuators A 8 (1985) 235–243.
[2] X. Ding, W.H. Ko, J.M. Mansour, Residual stress and mechanical properties of boron-doped p+ silicon films, Sens. Actuators A 21–23 (1990) 866–871.

[3] X.Y. Ye, Z.Y. Zhou, Y. Yang, J.H. Zhang, J. Yao, Determination of the mechanical properties of microstructures, Sens. Actuators A 54 (1996) 750–754.
[4] K.E. Petersen, C.R. Guarnieri, Young's modulus measurements of thin films using micromechanics, J. Appl. Phys. 50 (1979) 6761–6766.
[5] D. Walsh, B. Culshaw, Optically activated silicon microresonator transducers: an assessment of material properties, Sens. Actuators A 25–27 (1991) 711–716.
[6] L.M. Zhang, D. Uttamchandani, B. Culshaw, Measurement of the mechanical properties of silicon microresonators, Sens. Actuators A 29 (1991) 79–84.
[7] M. Hoummady, E. Farnault, H. Kawakatsu, T. Masuzawa, Application of dynamic techniques for accurate determination of silicon nitride Young's moduli, in: Proceedings of the International Conference on Solid-State Sensors and Actuators, Chicago, IL, June, 1997, pp. 615–618.
[8] L. Kiesewetter, J.M. Zhang, D. Houdeau, A. Steckenborn, Determination of Young's moduli of micromechanical thin films using the resonance method, Sens. Actuators A 35 (1992) 153–159.
[9] H. Majjad, S. Basrour, P. Delobelle, M. Schmidt, Dynamic determination of Young's modulus of electroplated nickel used in LIGA technique, Sens. Actuators A 74 (1999) 148–151.
[10] J.S. Burdess, A.J. Harris, D. Wood, R.J. Pitcher, D. Glennie, A system for the dynamic characterization of microstructures, J. Microelectromech. Syst. 6 (1997) 322–328.
[11] P. Fish, Physics and Instrumentation of Diagnostic Medical Ultrasound, Wiley, New York, 1990.
[12] D. Leedom, R. Krimholtz, G. Matthaei, New equivalent circuits for transducers having arbitrary even-or-odd-symmetry piezoelectric excitation, IEEE Trans. Sonics Ultrasonics SU-18 (1971) 128–141.
[13] C.S. Desilets, J.D. Fraser, G.S. Kino, The design of efficient broadband piezoelectric transducers, IEEE Trans. Sonics Ultrasonics SU-25 (1978) 115–125.
[14] G. Kossoff, The effects of backing and matching on the performance of piezoelectric ceramic transducers, IEEE Trans. Sonics Ultrasonics SU-13 (1966) 20–30.
[15] J. Souquet, P. Defranould, J. Desbois, Design of low-loss wide-band ultrasonic transducers for noninvasive medical application, IEEE Trans. Sonics Ultrasonics SU-26 (1979) 75–81.
[16] D.J. Ewins, Modal Testing: Theory and Practice, Research Studies Press, Letchworth, England, 1986.
[17] L. Meirovitch, Analytical Methods in Vibrations, Macmillan, New York, 1967.
[18] N. Guo, P. Cawley, The finite element analysis of the vibration characteristics of piezoelectric discs, J. Sound Vibr. 159 (1992) 115–138.
[19] N. Guo, P. Cawley, Transient response of piezoelectric discs to applied voltage pulses, Ultrasonics 29 (1991) 208–217.
[20] W.E. Newell, Miniaturization of tuning forks, Science 161 (1968) 1320–1326.

Biographies

Weileun Fang was born in Taipei, Taiwan, in 1962. He received his PhD degree from Carnegie Mellon University in 1995. His doctoral research focused on the determining of the mechanical properties of thin films using micromachined structures. In 1995, he worked as a postdoctoral research at Synchrotron Radiation Research Center, Taiwan. He is currently an associate professor at Power Mechanical Engineering Department, National Tsing Hua University, Taiwan. His research interests include MEMS with emphasis on microoptical systems, microactuators and the characterization of the mechanical properties of thin films.

Wen-Pin Lai was born in Taiwan in 1966. He received the MS degree in mechanical engineering from Chung Kung University, Tainan, Taiwan. He then worked at the Ultrasonic Technology Department of Industry Technology Research Institute (ITRI), Hsinchu, Taiwan. Meanwhile, he is engaged in the development of ultrasonic transducers for medical ultrasonic diagnostic application. He is currently studying for doctorate degree at Power Mechanical Engineering Department, National Tsing Hua University, Taiwan. His research focuses on the application of ultrasonic transducers for vibration testing of microstructures. His current interests are the development of the dynamic testing technology for microstructures.